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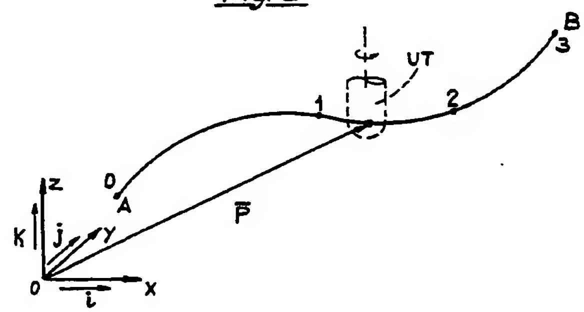
(54) Electronic polynomial interpolation device for numeric controls of machine tools, particularly milling machines for the machining of dies, and machine comprising said device.

(57) The device comprises a first section (25) , which comprises logic circuit means which generate the law of motion along the machine operative trajectory arc, and a second section with a set of three digital polynomial generators (27-28-29), each of which receives from the motion law generator means the instantaneous value of the curvilinear coordinate and, from an external processing unit, the polynomial coefficients related to the trajectory arc to be generated and the sampling and sub-sampling pulses; the polynomial generators of the second section are suitable for providing, on the respective outputs, the corresponding components of the instantaneous speed vectors of each point of the trajectory, generated by adding and multiplying the polynomial coefficients and the curvilinear coordinate.

Fig. 2



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ELECTRONIC POLYNOMIAL INTERPOLATION DEVICE FOR NUMERIC CONTROLS OF MACHINE TOOLS, PARTICULARLY MILLING MACHINES FOR THE MACHINING OF DIES, AND MACHINE COMPRISING SAID DEVICE

The present invention relates to an electronic polynomial interpolation device for numeric controls of machine tools, particularly milling machines for the machining of dies, and to a machine which comprises said device.

In the machining of metallic dies made of steel, cast iron or aluminum and intended for the production of articles made of sheet metal or plastic or composite materials, the completely automatic finishing of said die by means of machine tools has now become fundamentally important.

Manual restarting of the finishing operations is in fact a task which requires great specialization and very long times, with consequent unacceptable production costs.

In the design of dies, the appearance of computerized systems commonly known by the acronym CAD (Computer Aided Design) has allowed to mathematically define the surface of said die, regardless of its complexity, and to consequently generate parameters. When these parameters are processed by other computerized systems commonly known by the acronym CAM (Computer Aided Manufacturing), suitable for generating trajectories, they allow, by means of the numeric control system, to move the tool of the machines so as to reproduce the mathematically expressed surfaces.

The greatest disadvantage of these known automation systems currently consists of the interaction between the CAM systems and numeric controls due to the intrinsic limitations of the latter.

Currently known numeric controls in fact require the trajectory of the path of the tool, which is generated by a CAM system starting from the mathematical definition of the surface of the part to be machined, to be a broken line, generally with a large number of segments in order to contain chordal error. This, first of all, significantly limits the advancement speeds of the tool, which decrease as the allowed chordal error decreases and in any case become critical for values in the range of 10,000 mm/min due to the large amount of data to be processed.

The intrinsic nature of broken-line trajectories in any case leads, even if chordal error is kept within very narrow limits, to the generation of "faceted" surfaces which require the subsequent and undesirable manual finishing of the die.

The aim of the present invention is to eliminate these disadvantages, and, within the scope of this general aim, said invention has the important object of providing an electronic device which is suitable for directly interpolating tool trajectory arcs which are represented by polynomials of the n-th degree and are expressed as a function of a parameter, hereinafter termed curvilinear coordinate, which varies between zero and the length of said section of trajectory, thus obtaining corresponding continuous surfaces of the machined part which require no manual finishing intervention.

Another important object of the present invention is to provide a device which can significantly increase the tool movement speed and allow the acceleration and deceleration of the movement in the trajectory arc being considered, thus ensuring the correct blending together of contiguous arcs, even in the presence of blendings in which the surface has points of marked discontinuity (for example salient cusps).

A further object of the present invention is to provide an interpolation device which has a simple circuit structure, is highly reliable in operation and is suitable for being interfaced with any machine tool with at least three degrees of freedom and with any CAM trajectory generation system.

In order to achieve this aim, these important objects and others which will become apparent from the following detailed description, the present invention relates to an electronic polynomial interpolation device for numeric controls of machine tools, particularly milling machines for the machining of dies, characterized in that it comprises a first section which includes digital means for generating the law of motion and for calculating the curvilinear coordinate along the operative trajectory arc of the machine and a second section which comprises a set of three digital polynomial generators, each of which receives from the first section the instantaneous value of the curvilinear coordinate of the trajectory or portion of trajectory, the polynomial coefficients related to the trajectory arc to be generated, provided by an external processing unit and the sampling and sub-sampling pulses, the polynomial generators being suitable for providing, on their outputs, the corresponding components of the instantaneous position vector and of the instantaneous speed vector of each point of the trajectory calculated by adding and multiplying the polynomial coefficients and the curvilinear coordinate.

The first section generates a speed diagram according to the law of uniformly accelerated motion, along the ends of the trajectory arc being considered, by adding and subtracting constant-value acceleration steps by means of binary adders and accumulators.

In the second section, each polynomial generator comprises a register for the parallel accumulation of the polynomial coefficients, the serial output whereof is operatively connected to a chain which comprises an adder and an accumulator which, activated by the sub-sampling pulses, compute the polynomial which represents the trajectory reduced to a recursive form consisting of additions and multiplications.

The speed outputs of each polynomial generator are operatively connected, with the interposition of a register, of a digital/analog converter and of an operational amplifier, to the motor for the actuation of the tool along the respective coordinated axis. A fixed optical rule and an optical sensor moved by the drive shaft provide a datum which corresponds to the actual instantaneous position of the tool with respect to said axis; the actual position is compared with the theoretical one in order to obtain a positive or negative correction datum in terms of speed to be sent to the actuation motor.

Further characteristics, purposes and advantages will become apparent from the following detailed description and with reference to the accompanying drawings, given by way of non-limitative example, wherein:

figure 1 is a block diagram of an automatic numeric-control actuation system for a machine tool which comprises the polynomial generation device according to the present invention,

figure 2 is a diagram of a generic trajectory of the r-th degree followed by the tool of the machine of figure 1,

figure 3 is a block diagram of the interpolation device according to the invention,

figures 4, 5 and 6 are explanatory diagrams related to the first section of the interpolation device of figure 3,

figures 7 and 8 are detailed block diagrams of the first section of the interpolation device,

figure 9 is a detailed block diagram of one of the polynomial generators of the second section of the interpolation device,

figure 10 is a schematic view of a machine tool with three degrees of freedom and of the manner in which it is driven with the device according to the invention,

figure 11 is a detailed block diagram of the means for comparing the actual position with the theoretical position of the tool in order to generate a correction signal.

In the diagram of figure 1, the reference numeral 10 indicates a known CAD-CAM system for mathematically expressing generic surfaces and for generating tool trajectories starting from the mathematical definition of the surface.

The reference numeral 11 indicates a generic machine tool, for example a milling machine, which is operatively connected to the system by means of a microprocessor μP, an interface 12 provided with a memory, a control module 13 and the polynomial interpolation device according to the invention, which is generally indicated by the reference numeral 20. A programmable logic unit 15, controlled by the microprocessor μP, is furthermore provided for the auxiliary functions of the machine tool 11, such as cooling and lubrication pump management, temperature sensing and checking and the like, and programming of the speed of the tool-holder spindle.

The system 10 generates the trajectory of the tool in the form of numeric data and sends the data to the microprocessor μP, which stores them in the memory of the interface 12. By means of the same interface 12, the microprocessor μP sends the data to the interpolator 20 which, at discrete time intervals, generates the speed and position of the axes of the machine tool 11.

Depending on the actual position of the axes of the machine 11, the control module 13 corrects the position at discrete time intervals so that the trajectory followed by the tool is as close as possible to the theoretical one generated by the system 10.

Figure 2 illustrates a generic trajectory A-B which indicates the positions assumed in the course of time by the tool UT of the machine 11. A generic position of the tool is indicated by the vector $\bar{P}$ referred to a set of three Cartesian coordinates $\bar{x}$-$\bar{y}$-$\bar{z}$ and is expressed as follows:

$$\bar{P} = Px \cdot \bar{i} + Py \cdot \bar{j} + Pz \cdot \bar{k} \qquad (1)$$

where i, j and k are the unit vectors of the set of three Cartesian coordinates.

The components Px-Py-Pz of the vector are represented by respective polynomials of the r-th degree expressed as a function of a parameter "u" which is termed curvilinear coordinate and varies between 0 (zero) and the length of the trajectory:

$$P_x = a_{rx}u^r\ a_{(r+1)x}\ u^{r-1} + \dots a_{1x}\ u + a_{\o x}$$
$$P_y = a_{ry}u^r\ a_{(r+1)y}\ u^{r-1} + \dots a_{1y}\ u + a_{\o y}$$
$$P_z = a_{rz}u^r\ a_{(r+1)z}\ u^{r-1} + \dots a_{1z}\ u + a_{\o z} \qquad (2)$$

The degree r of the polynomial can be rather high (r >= 11) in the case of complex trajectories. The entire trajectory can however be divided into sub-trajectory portions of a degree m <= r; in particular, it is advantageous to divide the trajectory into portions represented by polynomials which can be expressed by means of expressions (2), in which m = 3 (cubic expressions).

The interpolator device 20 is provided, as input data, with the coefficients of the polynomials represented in (2), the curvilinear length of the sub-trajectory arc ${}_{i,i+1}S$, the speed ${}_{i,i+1}V$ at which the sub-trajectory is to be followed, the maximum acceleration ${}_{i,i+1}A$ allowed along the sub-trajectory and the squared exit speed ${}_{i,i+1}VQ_o$, as well as with

a percentage factor FP provided by the microprocessor μP.

Furthermore, since the system is of the sampled numeric type, the device 20 is also supplied with sampling pulses nT, where T is the sampling interval (for example T=1 ms), and with sub-sampling pulses sT; n is the set of integers comprised between $-\infty$ and $+\infty$ and $s=n+h/(m+1)$, where h varies between 0 (zero) and (m+1) with m equal to the degree of the polynomials to be generated.

With reference to figure 3 the device 20 substantially comprises a first section 25 which constitutes the generator of the law of motion along the trajectory arc and a second section composed of a set of three polynomial generators 27, 28, 29 which will be described hereinafter.

The task of the section 25 is to calculate, at discrete intervals nT, the position and the speed at the point $\overline{P}$ (nT). The notations of figure 4 are used; said figure illustrates a sub-trajectory arc i,i+1. The curvilinear coordinate ${}_{i,i+1}S(nT)$ is the position, at discrete intervals nT, of the vector $\overline{P}$ (nT) with respect to the origin of the arc i, the value ${}_{i,i+1}\overline{V}$ (nT) is the vectorial speed at discrete intervals nT; ${}_{i,i+1}\overline{V}_i$ and ${}_{i,i+1}\overline{V}_o$ are the vectorial speeds of input into and output from the sub-trajectory arc.

The law of motion along the sub-trajectory arc being considered is of the uniformly accelerated type and is plotted on speed and time coordinates in the diagram "δ" of figure 5.

A first logic circuit 30 (figure 7) of the first section 25 calculates the speed ${}_{i,i+1}\overline{V}$ (nT) at the instant nT and, by integrating said speed, calculates the value of the curvilinear coordinate u = ${}_{i,i+1}S(nT)$, the trend whereof is expressed in time by the curve "γ" of figure 6.

For this purpose, the logic circuit 30 comprises a first binary adder 31 which, at intervals nT, performs the sum between the speed V[(n-1)T] and the positive or negative acceleration steps ${}_{i,i+1}A+$, ${}_{i,i+1}A-$ present at the outputs of respective selectors 32-33.

The result of the sum operation is stored in an accumulator 34 so as to have available, at every instant, the speed datum related to the preceding instant. The accumulator 34 is reset at the beginning of each sub-trajectory. A second adder 35 integrates the speed V(nT) to obtain the curvilinear coordinate S(nT)=u by adding, at each instant nT, the speed V(nT) to the curvilinear coordinate related to the preceding instant (n-1)T stored in a respective second accumulator 36. A comparator 37 compares the curvilinear coordinate ${}_{i,i+1}S(nT)$ and the total curvilinear distance ${}_{i,i+1}S$ to recognize the end of the sub-trajectory arc and generate a signal ${}_{i+1}NA$ indicating a new arc. A multiplier circuit 38 furthermore calculates the square VQ(nT) of the speed V(nT) and a comparator 39 compares said squared value with a control value $VQQ_c(nT)$ which is calculated by a second logic circuit 40 (figure 8) of the section 25, in order to provide a criterion for the activation of the selector 32 or of the selector 33 depending on whether acceleration or deceleration is to be performed along the sub-trajectory being considered.

In order to calculate the control value VQQ_C (nT), having selected uniformly decelerated motion, in order to reach the quadratic value ${}_{i,i+1}VQ_o$ of the speed it is necessary to check, at each instant, that the difference

${}_{i,i+1}VQ(nT) - {}_{i,i+1}VQ_o$

is always smaller than twice the product of the acceleration ${}_{i,i+1}A$ and the space $[{}_{i,i+1}S]-[{}_{i,i+1}S(nT)]$ which is still to be lowered to end the sub-trajectory arc, and it is necessary to decelerate if the difference between said squared speed exceeds the indicated value.

This check is performed by the circuit 40, wherein a binary subtractor 41 performs the subtraction $[{}_{i,i+1A}S]-[{}_{i,i+1}S(nT)]$, and a first binary multiplier 42 performs the product of the subtraction and of the acceleration ${}_{i,i+1}A$ which has been pre-multiplied by two in a binary duplicator 43. An adder 44 adds the output value of the multiplier 42 to the square of the speed ${}_{i,i+1}VQ_o$ of output from the sub-trajectory arc, and two multiplier circuits 45, 46 calculate the square of the product between the maximum allowed speed ${}_{i,i+1}V$ and the percentage factor FP.

A comparator 47 compares the outputs of the adder 44 and of the multiplier 46 and drives two selectors 48, 49 which always give the comparison value ${}_{i,i+1}VQQ_c(nT)$ the smallest of the two values which input said comparator.

The output u = ${}_{i,i+1}S(nT)$ of the first section 25 is multiplexed at the input of the polynomial generators 27, 28, 29 which compose the second section of the device 20; each of the generators has the purpose of generating discrete positions and discrete speeds for each of the axes X, Y and Z along which the tool UT of the machine 11 moves.

For this purpose, each polynomial generator comprises a logic circuit 50, which is illustrated in detail in figure 9, and which, by successive sums and multiplications of the polynomial coefficients and of the curvilinear coordinate, calculates the respective polynomial (2) reduced to the following recursive form (for r=3):

$${}_{i,i+1}P_x = [({}_{i,i+1}a_{3x}u + {}_{i,i+1}a_{2x}).u + {}_{i,i+1}a_{1x}].u + {}_{i,i+1}a_{\emptyset x}$$

and likewise for the components Py and Pz.

The circuit is substantially composed of a shift register 51 in which the coefficients of the polynomial to be generated are accumulated in parallel and at each sampling instant nT; in the case of a cubic polynomial, the coefficients are of the follow-

ing type:

$_{i,i+1}a_{3x}$; $_{i,i+1}a_{2x}$; $_{i,i+1}a_{1x}$; $_{i,i+1}a_{\emptyset x}$.

The sub-sampling pulses sT (in the case of m = 3, a cubic polynomial, four sub-sampling pulses for each sampling pulse) also input the register 51. At each sub-sampling pulse sT, a coefficient of the polynomial inputs a binary adder 52 starting from $_{i,i+1}a_{3x}$ and followed, in the subsequent sub-sampling intervals, by

$_{i,i+1}a_{2x}$; $_{i,i+1}a_{1x}$ and finally by $_{i,i+1}a_{\emptyset x}$.

A binary multiplier 53 performs, again at each sub-sampling interval, the product of the curvilinear coordinate u = $_{i,i+1}S(nT)$ and of the output value of the adder 52 at the preceding instant, which is stored in an accumulator 54; the accumulator 54 is reset at each sampling interval nT by a reset pulse R. In this manner, the polynomial Px reduced to its recursive form is calculated at each sampling cycle nT.

A first register 55 and a second register 56, as well as a binary subtractor 57, are arranged at the output of the binary adder 52. The datum of theoretical position P_{tx} (nT) is taken from the first register 55. The theoretical speed datum V_{tx} (nT) is taken from the output of the subtractor 57 and is obtained by means of the subtraction of the position at the instant nT from the position at the preceding instant (n-1)T which is performed by said subtractor 57.

As shown in detail in figure 10, the outputs $V_{tx,y,z}(nT)$ of the polynomial generators 27, 28 and 29 feed, with converter and amplifier units CAx, CAy, CAz interposed, respective motors Mx, My, Mz of the machine tool. Each converter and amplifier unit comprises a register 60, a digital/analog converter 61 and a multi-stage operational power amplifier 62 feedback by a speedometer generator Dx, Dy, Dz actuated by the respective motor.

The motor Mx is associated with a movement unit GMx which is rigidly coupled to the base BA of the machine and comprises a ball bearing nut CHx which is moved: along the x axis, by a worm screw VSFx which is moved by the motor Mx.

Similarly, the motor My is associated with an identical movement unit GMY which however, differently from the unit GMx, is movable along the y axis and is moved along the y axis by the nut CHx of the unit Mx. In turn, the nut CHy of the unit GMy, which is movable along the y axis and is actuated by the screw VSFy, moves the entire unit GMz along the z axis; the tool UT which generates the die ST, is supported in a known manner by a mandrel which rotates at a programmed speed, and it is rigidly associated with the nut CHz which is also movable along the z axis and is actuated by the screw VSFz.

A micro-line optical rule REx, REy and REz is rigidly associated with the frame of each movement unit, and a respective optical sensor SOx, SOy, SOz co-operates with each rule; the signals of the sensors SOx, SOy, SOz are converted, by means of respective position counters $70_{x,y,z}$ and registers $71_{x,y,z}$, into a datum which corresponds to the actual positions Px(nT), Py(nT) and Pz(nT) of the tool. A set of three logic circuits 80 compares the actual positions with the theoretical ones calculated by the polynomial generators 27, 28, 29 in order to generate a correction signal $V(nT)_{x,y,z}$ in terms of speed.

For this purpose, as illustrated in the detail of figure 11, each circuit 80 comprises a subtractor 81 which calculates the difference between the theoretical position and the actual one, a multiplier 82 which performs the product of the result of the subtraction and of the gain $G_{x,y,z}$ of the respective control loop, and an adder 86 which adds the respective theoretical speed $Vt_{x,y,z}(nT)$ at the instant being considered to the result of said product.

Without altering the concept of the invention, the details of execution and the embodiments may naturally be varied extensively with respect to what is described and illustrated by way of non-limitative example without thereby abandoning the scope of the invention.

In particular, the device 20 might be replaced with a single sequential logic unit, for example a microprocessor programmed to generate the law of motion along the arc or sub-ares of the machine operative trajectory, to integrate the speed diagram related to said law of motion, to obtain the curvilinear coordinate of said trajectory, and to calculate the polynomial which represents the trajectory reduced to a recursive form of additions and multiplications.

Where technical features mentioned in any claim are followed by reference signs, those reference signs have been included for the sole purpose of increasing the intelligibility of the claims and accordingly such reference signs do not have any limiting effect on the scope of each element identified by way of example by such reference signs.

Claims

1. Polynomial interpolation device for numeric controls of machine tools, particularly milling machines for the machining of dies, characterized in that it comprises a first section which includes logic circuit means for generating the law of motion along the machine operative trajectory arc and a second section with a set of three digital polynomial generators, each of which receives from the motion law generators the instantaneous value of the curvilinear coordinate and, from an external processing

unit, the polynomial coefficients related to the trajectory arc to be generated, and the sampling and sub-sampling pulses; the polynomial generators of the second section being suitable for providing, on the respective outputs, the corresponding components of the instantaneous position vectors and of the instantaneous speed vectors of each point of the trajectory, generated by addition and multiplication of the polynomial coefficients and of the curvilinear coordinate.

2. Device according to claim 1, characterized in that said first section generates a speed diagram according to the law of uniformly accelerated motion across the ends of the trajectory arc being considered.

3. Device according to claim 2, characterized in that the logic circuit means of the first section generate the speed diagram by adding or subtracting constant-value acceleration steps.

4. Device according to claim 1, characterized in that the logic circuit means of the first section are suitable for calculating the instantaneous value of the curvilinear coordinate of the trajectory by integrating the diagram of the speed which represents the law of motion.

5. Device according to claim 1, characterized in that the polynomial coefficients related to the trajectory arc to be generated are produced by a microprocessor-based external auxiliary system capable of mathematically defining a surface.

6. Device according to claims 1 to 4, characterized in that the logic circuit means of said first section comprise a first binary adder which performs, at each sampling interval, the sum of the speed related to the preceding instant and of the positive or negative acceleration steps which are preset at the outputs of respective selectors, a first binary accumulator in which the value of the sum is stored, a second binary adder which integrates the speed related to a given instant by adding to said speed the curvilinear coordinate related to the preceding instant, which is stored in a second binary accumulator, and a binary comparator which compares the curvilinear coordinate at the instant being considered and the total curvilinear distance in order to recognize the end of the trajectory arc and to generate a signal indicating a new arc.

7. Device according to claim 6, characterized in that said logic circuit means of the first section furthermore comprise a binary multiplier circuit which is suitable for calculating, at each sampling interval, the square of the generated speed, and a binary comparator which compares said squared value with a control value to provide a criterion for activating said selectors depending on whether acceleration or deceleration is to be performed along the sub-trajectory being considered.

8. Device according to claims 6 and 7, characterized in that the logic circuit means of said first section furthermore comprise a logic circuit for generating said control value which comprises a binary subtractor which subtracts, at each sampling interval, the length of the sub-trajectory arc from the curvilinear coordinate, a first binary multiplier which performs the product of said subtraction and of twice the acceleration step, a binary adder which adds the output value of the multiplier to the square of the speed of exit from the sub-trajectory arc, two further binary multipliers which calculate the square of the product of the maximum allowed speed and of a percentage factor, and a digital comparator which compares the output of the first multiplier with that of the adder to drive two selectors which assign the lowest of the two values which enter said comparator to the comparison value.

9. Device according to claim 1, characterized in that each polynomial generator of the second section comprises a shift register for the parallel accumulation of the polynomial coefficients and wherein the serial output of the shift register is operatively connected to a chain which comprises a binary multiplier, a binary adder and a binary accumulator which are suitable for calculating the polynomial which represents the trajectory reduced to a recursive form of additions and multiplications of the polynomial coefficients and of the curvilinear coordinate.

10. Device according to claim 6, characterized in that the length of the registers of the polynomial generators is proportionate to the degree of the polynomial to be generated and is equal to the degree of said polynomial + 1.

11. Device according to claim 9, characterized in that the polynomial coefficients are accumulated in the shift register at each sampling interval and are transferred in a scalar manner to the binary adder at each sub-sampling pulse.

12. Device according to claim 10, characterized in that the binary multiplier performs, at each sub-sampling interval, the product of the curvilinear coordinate and of the output value of the adder related to the preceding interval, which is stored in said accumulator.

13. Device according to claim 1 and any one of the preceding claims, characterized in that it comprises a microprocessor which is programmed to generate the law of motion along the machine operative trajectory arc, to integrate the speed diagram related to said law of motion, to obtain the curvilinear coordinate of said trajectory and to calculate the polynomial which represents the trajectory reduced to a recursive form of additions and multiplications.

14. Machine tool, particularly milling machine for the machining of dies, characterized in that it comprises a polynomial interpolator interfaced on one

side with a system for generating polynomial coefficients and with said machine tool on another side, and in that the polynomial interpolator comprises a first section, which generates the curvilinear coordinate of the trajectory arc of the machine tool by integrating the speed diagram related to the preset law of motion, and a second section with a set of three polynomial generators, each of which comprises a multiplier, an adder and an accumulator which are suitable for calculating the polynomial which represents the trajectory of said tool reduced to a recursive form of additions and multiplications.

15. Machine tool according to claim 14, characterized in that the theoretical speed outputs of the polynomial generators drive, with converter and amplifier units interposed, the motors of respective units for moving the machine tool, and in that each movement unit comprises a rule and an optical sensor which co-operate and are suitable for providing the actual position of the tool along the related coordinated machine axis and a set of three logic circuits inserted in respective control loops, each of which compares the actual positions along the corresponding machine axis with the theoretical ones provided by the polynomial generators in order to generate a corresponding correction signal in terms of speed.

16. Machine tool according to claim 15, characterized in that the logic circuit of each control loop comprises a binary subtractor which calculates the difference between the theoretical position and the actual one, a binary multiplier which multiplies the result of the subtraction by the gain of the respective control loop, and an adder which adds the respective theoretical speed at the instant being considered to the result of said product.

Fig. 1

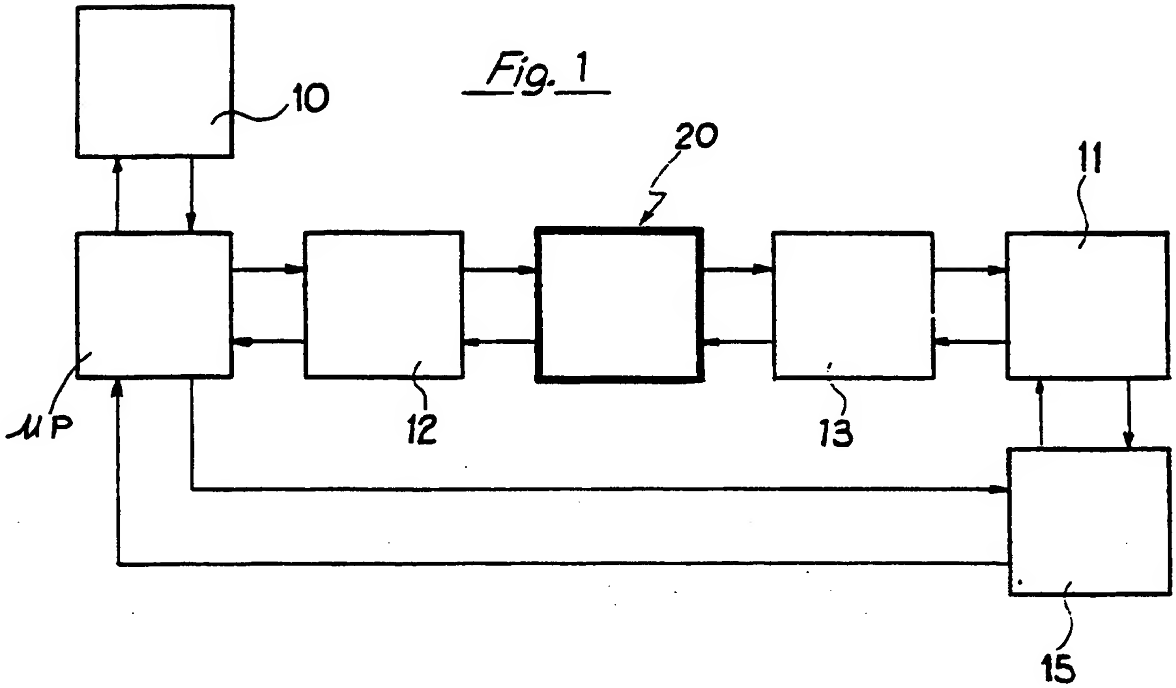

Fig. 2

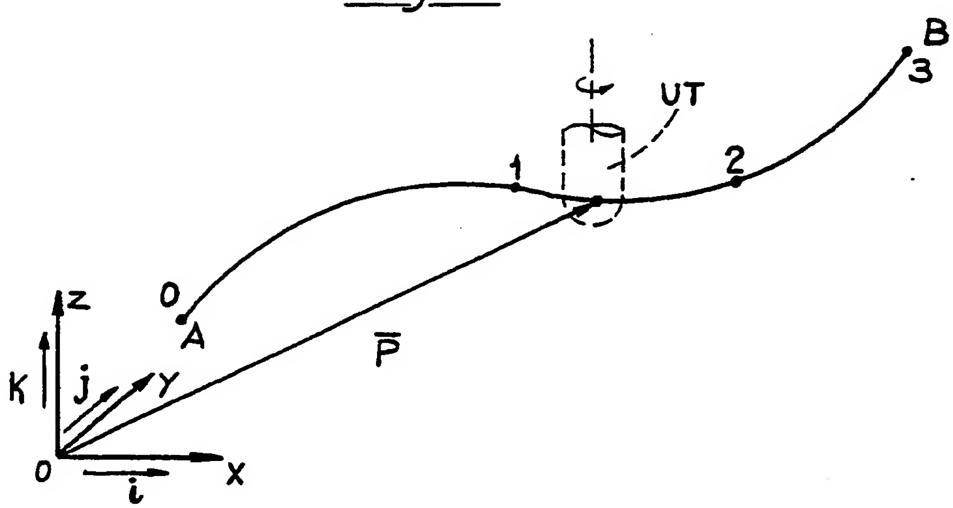

Fig. 3

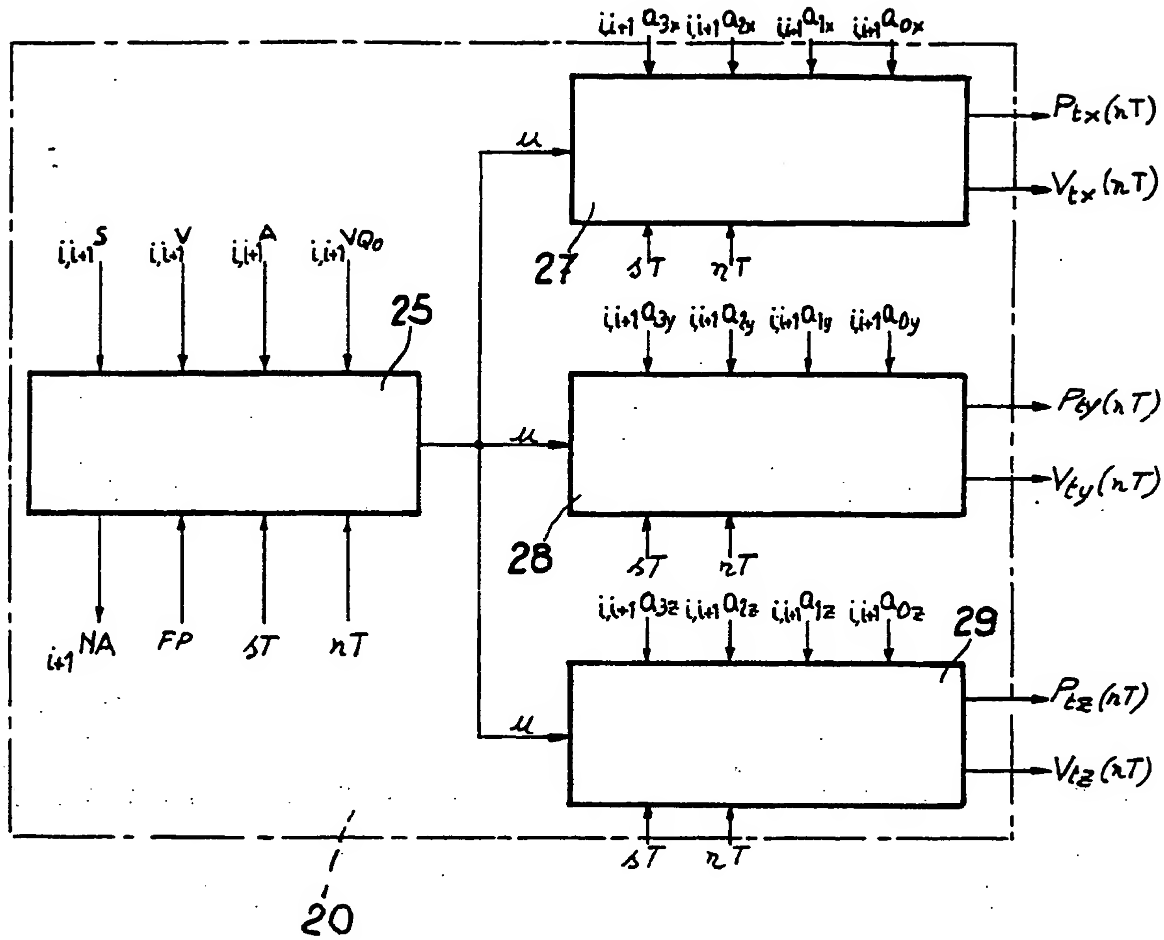
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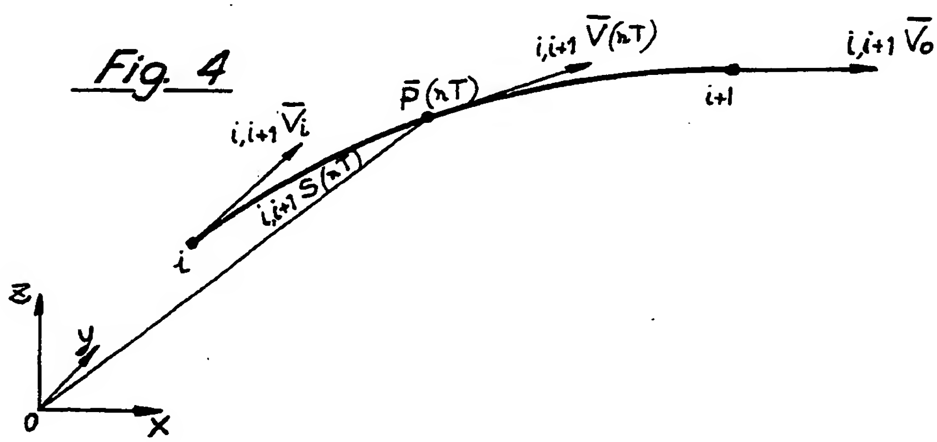
Fig. 4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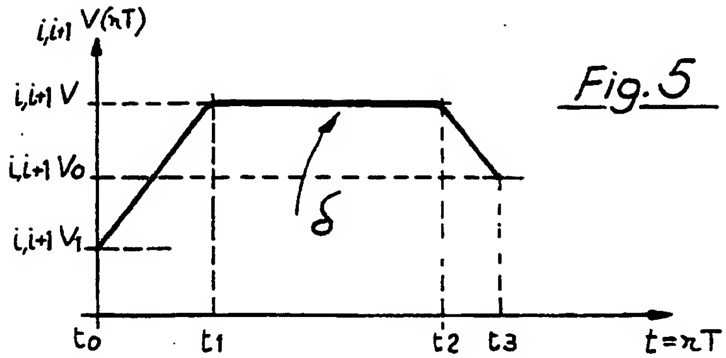


Fig. 5

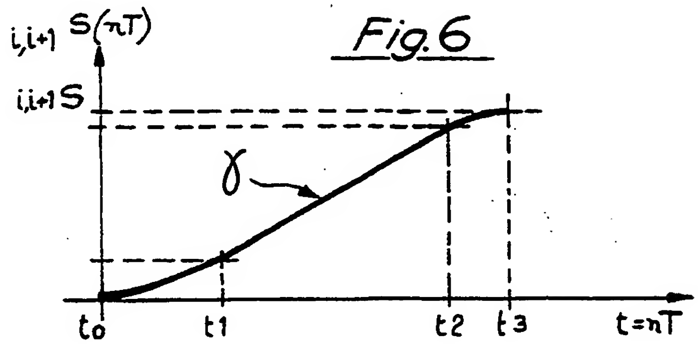


Fig. 6

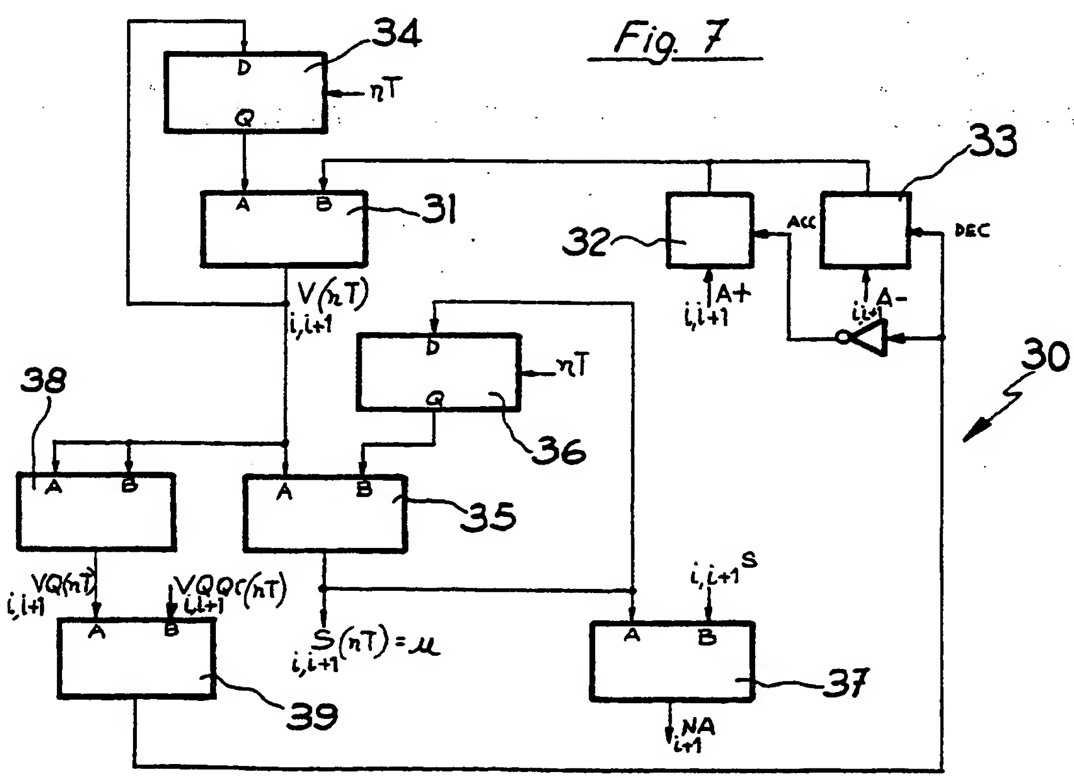


Fig. 7

Fig. 8

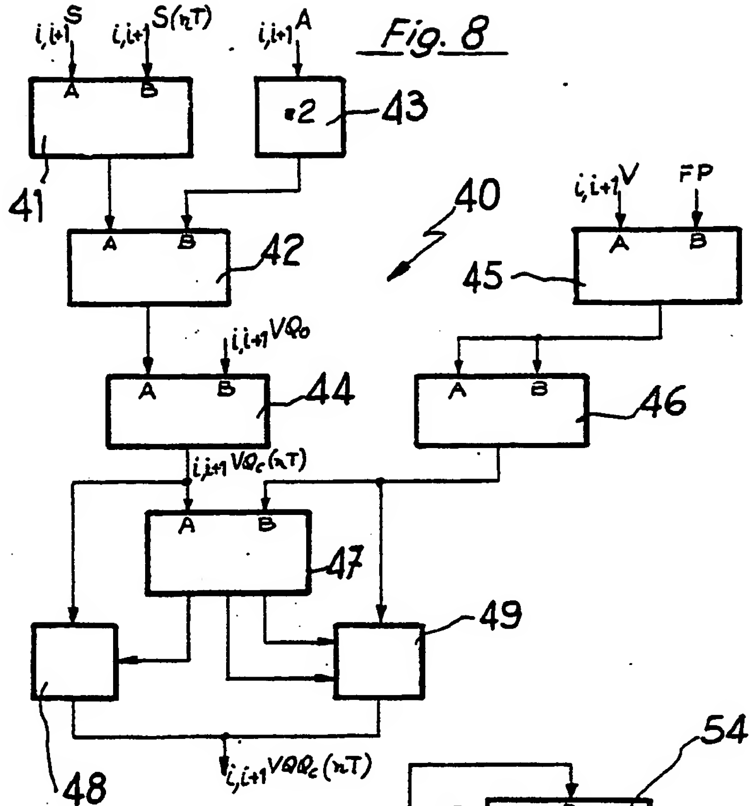


Fig. 11

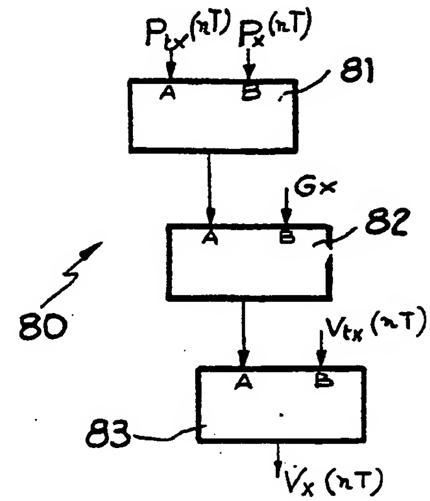


Fig. 9

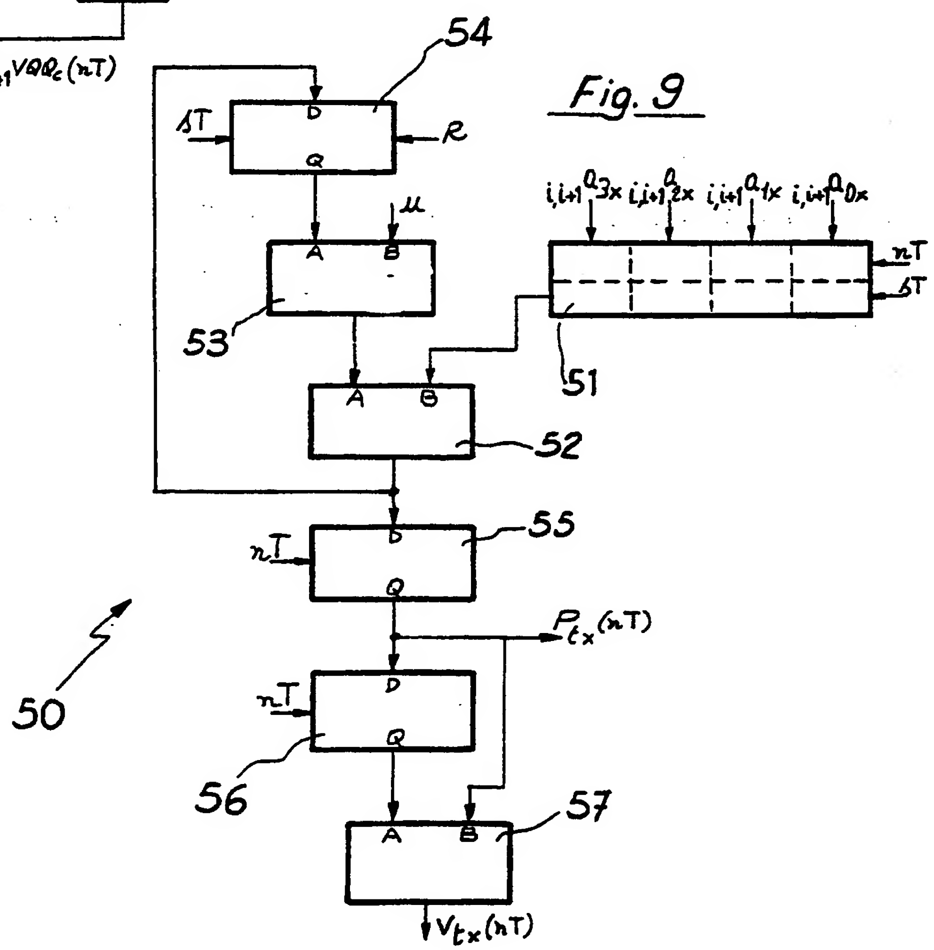
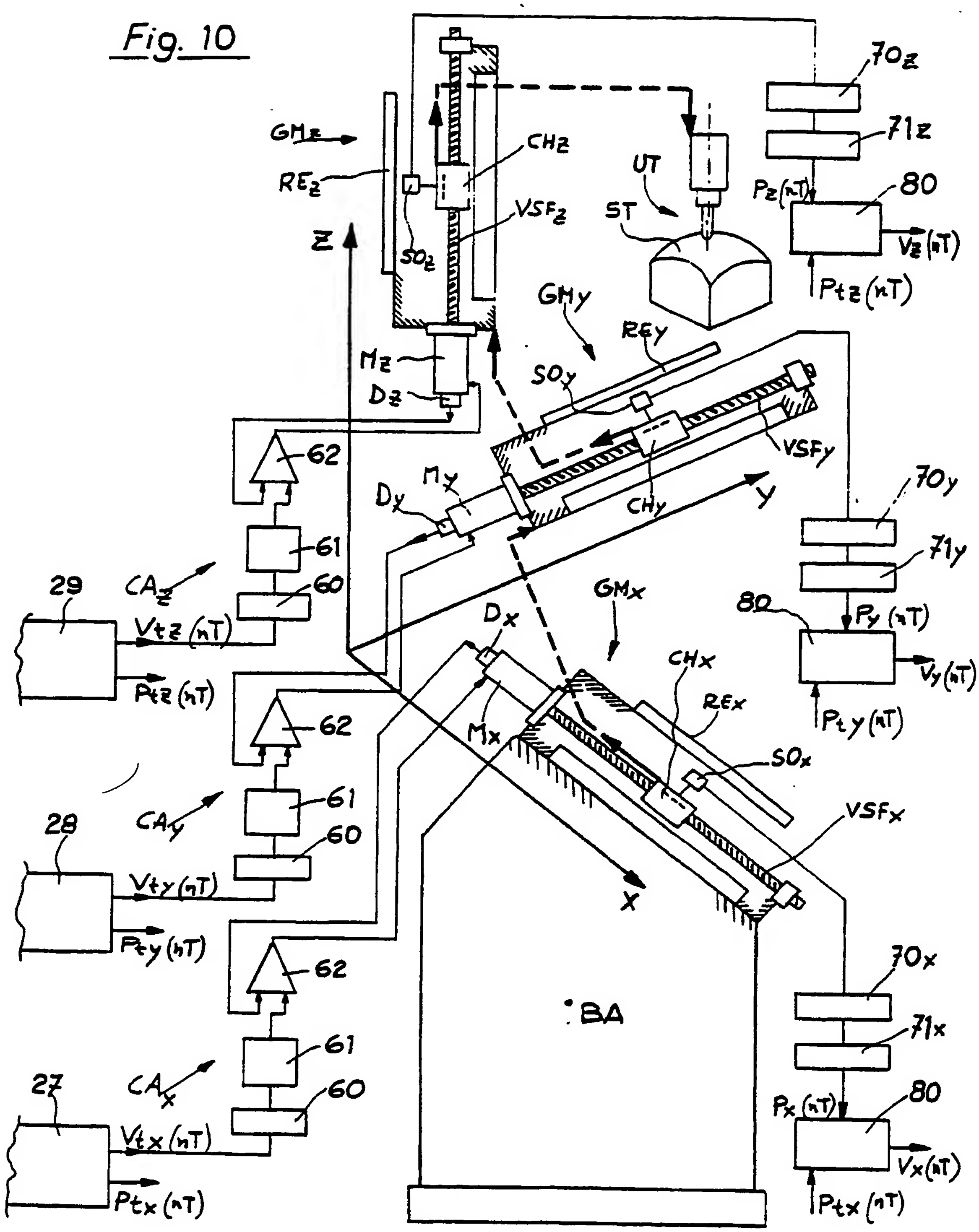


Fig. 10


70z
71z
GMz
CHz
REz
UT
Pz(nT)
80
VSFz
ST
Z
SOz
Vz(nT)
Ptz(nT)
GMy
REy
Mz
SOy
Dz
62
VSFy
My
Dy
CHy
Y
70y
61
71y
29
CAz
60
GMx
80
Py(nT)
Dx
Vtz(nT)
Ptz(nT)
CHx
Vy(nT)
REx
62
Mx
Pty(nT)
SOx
61
CAy
28
60
VSFx
Vty(nT)
X
Pty(nT)
62
70x
BA
71x
61
27
CAx
60
Px(nT)
80
Vtx(nT)
Vx(nT)
Ptx(nT)
Ptx(nT)